

CRYOGENIC ENGINEERING, PRODUCTION AND USE OF INDUSTRIAL GASES

STIRLING MACHINES FOR HIGH-EFFICIENCY AND ECOLOGICALLY CLEAN STAND-ALONE ENERGY SUPPLY SYSTEMS

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Gas regenerative machines operating on forward and reverse Stirling cycles (Stirling machines) [1] are the most promising ecologically clean energy converters which meet the requirements of energy generation with minimum use of material resources. Structurally, Stirling machines contain in a single unit a compressor, an expander, and heat-exchanging devices (heater or condenser, regenerator, and refrigerator). The working medium used is generally helium which executes in the inner loop (circulatory system) of the machine forward or reverse thermodynamic cycle consisting of two isotherms and two isochores. The advantages of Stirling machines include a number of fundamental properties which are unique to only these machines:

- universality of the thermodynamic cycle itself, which allows one to build forward- and reverse-cycle converters of various designs;
- maximum energy efficiency (the theoretical efficiency of the cycle of an ideal Stirling machine equals the efficiency of a Carnot's cycle);
- high degree of ecological cleanness of both the working media of the Stirling machines themselves and the waste media;
- possibility of use of local raw materials and unconventional sources of heat, e.g., solar energy (radiation), natural gas, peat, coal, etc.

The referred properties of the Stirling machines can be used to build on their basis various stand-alone energy supply systems which may be divided into several groups in terms of their functional purpose.

Electric power generation system: stand-alone power supply systems based on Stirling engines, systems that utilize low-potential waste heat, e.g., power plants having Stirling liquid-piston engines of the Fluidyne type, anaerobic (not dependent on air) stand-alone power supply systems of special facilities, atomic power plants based on Stirling engines, etc.

Systems utilizing moderate refrigeration: stand-alone refrigeration supply systems based on moderate-refrigeration Stirling machines for stationary facilities and autorefrigeration engineering, centralized and stand-alone air conditioning systems, etc.

Systems utilizing deep refrigeration: stand-alone cryogenic refrigeration supply systems, natural gas liquefaction systems, nitrogen liquefaction systems, oxygen liquefaction systems, long-term cryogenic fuel storage systems, systems for control of temperature of special objects, systems for fast freezing and storage of food products, systems for recovery of light hydrocarbons during storage of oil and oil products, etc.

Heat generating systems: decentralized heat supply systems based on Stirling heat pumps, cogenerative plants for simultaneous generation of electric power and heat based on Stirling engines, etc.

Wide application of Stirling machines is impeded by a lack of theory and calculation methods owing to complexity of mathematical description of the processes occurring in the inner loop of the machines.

Theoretical and experimental studies have been carried out at the VIKU im. A. F. Mozhaiskogo (A. F. Mozhaiskii Military Space Engineering University) to create stand-alone energy supply systems based on machines of a given cycle. Proce-

dures have been worked out for calculation and multiparametric optimization of Stirling machines to attain an efficiency matching the best foreign versions of such machines. Patent research and analysis of invention and innovation activities are being carried out at more than 80 companies of the world which are engaged in development of Stirling machines [2]. Special attention is being focused on the analysis of the design of the main units of the Stirling machines as well as on development of new designs of functionally different plants. Patents have been obtained for many of the proposed designs.

Practical experience has shown that sound designing may greatly reduce the cost of Stirling machines in both prototype and series-produced versions. The results achieved have created real grounds for wide application of Stirling machines virtually in all branches of national industry and engineering.

Engine Making and Stand-Alone Power Sources Based on Stirling Generators. Stirling engines have great potentials for further development. Low noise level, low toxicity of the waste gases, ability to operate on different types of fuels, long service life, comparable size and mass, adequate torque, etc., are the parameters of the Stirling heat machines (engines) that are superior to those of internal combustion engines (ICE) [3].

At this time, Stirling engines are being widely applied in military engineering. For instance, during 1996–1997, Sweden launched into production a series of submarines that have anaerobic installations with Stirling engines up to 100 kW in power. The engines were made by United Stirling and have an efficiency of more than 38%. The Japanese company Mitsubishi has successfully tested a 600 kW Stirling engine for Harushio type of submarines, in Germany a Stirling engine with a power of more than 700 kW has been built for submarines, and so on. Stirling engines of smaller power (up to 50 kW) having an efficiency of up to 35% are being serially produced by a number of foreign companies.

A Stirling engine, where the heat is supplied from outside, differs from an internal combustion engine (ICE) in that the combustion process occurs outside the working cylinders and is more equiponderant, the working cycle is executed in a closed internal loop (inner circulation space) at a relatively slow rate of pressure rise in the engine cylinders, and the thermohydraulic processes of the working medium of the internal loop occur smoothly in the absence of gas distribution mechanism of the valves.

Natural gas and hydrogen are considered the most promising fuels for transport facilities and stationary power (energy) plants having Stirling engines because of their high energy indices and virtually limitless availability in Russia. Use of these energy carriers as fuels will make it possible to raise the efficiency of Stirling engines (on account of heightened upper temperature of the cycle) and to reduce the concentration of deleterious substances in the combustion products virtually to the minimum.

Because of steep rise in price of liquid hydrocarbon fuels (residual fuel oil, gasoline, diesel fuel, etc.), the possibility of serial manufacture of power generators from 3 kW to 500 kW in capacity, with modification of the Stirling engine for use of local fuel, is of considerable interest to Russia as well. Peat, pulverized coal, shales, agricultural and wood-processing wastes, etc. may be used as local fuels for Stirling generators.

Technology of Moderate Refrigeration. Refrigeration engineering is an indispensable aspect of life of every human being. It is difficult to think of life in modern cities, development of the food industry and trade, etc. without refrigerators of various capacities. Moderate refrigeration (cooling) is used for air conditioning residential and industrial buildings.

Nowadays, for general and industrial refrigerating as well as air conditioning plants, essentially vapor-compression refrigerating machines are used because of several favorable properties unique to these machines, e.g., relatively high efficiency, simple element base, etc. However, the refrigerants usable in these refrigerating machines as working media produce a significant effect on the development of critical situations in the ecological domain (disruption of the ozone layer of the earth and greenhouse effect). The state statutory acts adopted in recent years, which include the Government of Russia Resolution No. 378 of June 3, 1992, entitled Measures for Ensuring Fulfilment of the Obligations of the Russian Federation under the Vienna Convention on Protection of the Ozone Layer and the Montreal Protocol on Ozone Depleting Substances as well as the Decision of the Government of the Russian Federation of May 5, 1999 on cessation of production of ozone-depleting substances from June 1, 2000, require the industry and science to create new high-efficiency and ecologically clean refrigerating machines.

Machines operating on reverse Stirling cycle have the referred characteristics. These refrigerating machines are highly efficient, there being no internal losses in them. Technical losses due to finite temperature difference during external and internal heat exchange as well as due to friction diminish substantially if the designs used are optimum and the mathematical apparatus applied is precise [4, 5].

Stirling refrigerating machines for moderate refrigeration have been developed and are on way to serial production abroad for commercial refrigeration plants (Germany) and pistonless refrigerating machines for home refrigerators (USA, South

Korea). In Russia as well, enough experience has been gathered in developing moderate-refrigeration Stirling machines [6]. The research data will help create refrigerating machines of the referred cycle 1.5 times as efficient as the existing vapor-compression refrigerating machines [7].

Deep-Refrigeration Engineering (Cryogenic Engineering). Stirling cryogenic gas machines (CGM) have gained wide popularity in microcryogenics, cryomedicine, and industrial gas liquefaction plants. Of special interest at this time is development of new technologies where the potentials of Stirling machines may be particularly tangible. Such technologies include natural gas liquefaction and storage systems, new liquid oxygen and nitrogen production cycles, systems for recovery of light hydrocarbon fractions during storage of oil products, systems for long-term storage of cryogenic fuel of anaerobic systems of stand-alone energy supply of special facilities, systems for fast freezing and storage of food products, systems for stand-alone cryogenic refrigeration supply, and many other directions that have developed at the turn of the 21st century.

The Stirling cryogenic gas machines created and serially produced by Philips (Holland) and the open joint-stock company Arsenal Machine Building Plant (St. Petersburg) are in wide use as small-capacity (5–300 kg/h) atmospheric air liquefiers and for producing liquid oxygen and nitrogen. These machines can be used also for liquefaction of gases having a higher condensation temperature, e.g., ethane, propylene, propane, etc. In Russia, production of Stirling cryogenic gas machines is being pursued by the scientific and production association Geliimash (Helium Machinery) which has developed prototypes of the nitrogen production plant Azh-0.05 having Stirling cryogenic gas machines producing more than 50 kg/h of liquid nitrogen as well as by the open joint-stock company Sibirkriotekhnik (Siberian Cryogenic Engineering) which has been developing and producing microcryogenic equipment [6, 8].

One of the most promising lines of application of Stirling CGM is creation of small-capacity compact plants for liquefied natural gas (LNG) production, which will be of great help in solving the problem of conversion of automobile transport to cheaper types of fuel and LNG supply to the population. The advisability of creation of such plants stems as well from the fact that the well-known Stirling CGM are most efficient at around 110 K, i.e., at the temperature of phase transition of gaseous natural gas into liquid. At this temperature level the efficiency of the natural gas liquefaction cycle in Stirling CGM is 2–2.5 times as high as when simple throttle and expansion cycles of a comparable efficiency are used [4].

Decentralized Heat Supply. In order to develop decentralized heat supply with maximum proximity of the heat sources to the consumers, it is advisable to introduce heat pumps. Abroad, application of heat pumps has made it possible to reduce consumption of fuel resources by 10% annually through utilization of low-potential waste heat of the surrounding medium.

With the aid of heat pumps operating on reverse Stirling cycle, it is possible (at a specific consumption of 1 kW of useful power for pump driving) to get 3–7 kW of heat at the output. Stirling heat pumps may be used for heat supply of buildings and structures being built afresh or will be rebuilt; they are particularly effective for equipment in dispersed buildings, for example, farmlands, customs and border stations, cottages and isolated buildings, etc.

The fundamental difference of Stirling heat pumps from vapor-compression, absorption, and heat pumps of other types is that the working medium of Stirling heat pumps does not change its aggregate state throughout the cycle. These heat pumps allow use of the surrounding air as low-potential heat at temperatures below 240 K and heating of the heat carrier of the heat supply system above 370 K. The advantages of Stirling heat pumps also include higher thermodynamic efficiency and use of ecologically clean working media [9].

Another line of decentralized heat supply is application of cogeneration plants (CP) that provide for combined generation of electric power and heat based on stand-alone engines and heat recuperation system where the energy of cooling water and waste gases is utilized for heat supply to consumers. The effectiveness of application of Stirling engines in CP vis-à-vis ICE stems from the peculiarity of its heat balance expressed in the difference of heat losses with the waste gases and to the cooling water. For Stirling engines, these indices are respectively 10 and 40%, which, because of higher efficiency of the engine itself, makes it possible to create compact and high-efficiency CP.

Oil, Gas, and Coal Industry. To this day, the problem of utilization of associated petroleum gas has not been resolved in the oil industry. According to some estimates, as much as 10 billion cubic meters of associated gas are burnt in Russia alone. A similar situation has developed in the coal industry as well. For instance, in the countries of the CIS (Commonwealth of Independent States), the degassing installations annually recover from coal mines more than 2.3 billion cubic meters of methane, which include 900 million cubic meters in Russia, i.e., there are wide scopes for application of Stirling engines for utilization of associated gases.

Stand-alone power plants having Stirling engines (Stirling generators up to 100 kW in capacity) operating on methane, natural gas, and associated gas may be used for power supply to townships of oil and gas workers and geologists. These plants

are highly efficient and ecologically clean and have a low noise level, which allow them to be located in the immediate vicinity of consumers. As a result, there is no need for expensive fuels and no loss on long-distance power transmission.

It is advisable to create CP on the basis of Stirling generators that provide for generation of both electric and heat energy for heating as well as for industrial and municipal needs. Stirling generators 3–10 kW in power are beneficial to apply in automation systems, communications, and cathodic protection in trunk pipelines. Thus, use of Stirling generators operating on cheap local gas have enormous advantages over well-known stand-alone energy plants based on ICE and electrochemical generators.

Space Engineering. Research done by several foreign companies, which include NASA, British Aerospace Public Company, etc., validates the expediency of application of Stirling machines for creation of stand-alone energy supply systems for orbital space stations (OSS). Stirling engines have been designed that use solar and nuclear energy. The “solar” Stirling engines built have by now a net efficiency of more than 30%. Moderate-refrigeration Stirling machines designed for medical and biological research have passed through summer test cycles in the course of implementation of the Space Shuttle Program.

The results of many years of research conducted by the specialists of the A. F. Mozhaiskii Military Space Engineering University prove that it is possible to create for space research a new class of energy systems, viz., energorefrigerating systems (ERS) which represent structurally functional unification of forward- and reverse-cycle converters designed for combined generation of electric power and refrigeration at a fixed temperature level. The experimental data show that application of Stirling machines having high thermodynamic efficiency makes it possible to significantly reduce the volumes of the material media inside orbital space stations and to increase the period of their self-reliance.

Nuclear Energy. Nuclear energy is widely used in various branches of the industry and in special techniques, but the problems of enhancing safety of nuclear reactors and final burial of radioactive wastes have not yet been solved; it is necessary to formulate measures for discontinuance of operation of spent-up reactors, creation of a reliable and inexpensive closed fuel cycle, etc.

Creation of small-capacity (up to 5000 kW) power plants based on gas-cooled fast-neutron reactors or liquid-salt reactors having Stirling engines is opening up fundamentally new possibilities of producing ecologically clean nuclear energy. The specialists at the Military Space Engineering University have developed several designs of such power plants. A distinctive feature of these designs is the high degree of their ecological safety and the scope for application of helium for reactor cooling (helium is the only heat carrier that does not become radioactive).

Application of liquid-type reactors based on melting of salts of radioactive substances (fluorides of U-235, Th-233, and lithium) is a new direction in nuclear energy utilization and may turn out to be an alternative to existing small-capacity nuclear reactors. The gaseous heat carrier (helium) fed into the melt layer at various pressures carries away the heat and energy of the nuclear reactors from the melt. The used salt melt can be easily processed by pyrometallurgical techniques.

In concluding, it must be stated that application of ecologically clean and high-efficiency machines operating on forward and reverse Stirling cycles in stand-alone energy supply systems is the most radical direction in solving problems of fuel resource saving and reducing environmental pollution.

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